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PERFORMANCE OF N/P SILICON AND CADMIUM SULFIDE SOLAR CELLS AS AFFECTED BY HYPERVELOCITY PARTICLE IMPACT

by Robert L. Bowman, Michael J. Mirtich, and John R. Jack

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Cleveland, Ohio

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ABSTRACT

A shock tube was used to accelerate particles to hypervelocities for the purpose of simulating micrometeoroid exposure. Various solar cells were then exposed to this simulated environment. The electrical characteristic curves of the cells before and after exposure were measured. The degradation of N/P Si solar cells covered by the thinnest quartz (6 mils or 0.15 mm) was greatly reduced from that suffered by cells without covers. The studies also demonstrated that encapulated CdS solar cells performed as well as protected silicon for exposure energies less than 0.5 J despite evidence of particle penetration of the encapsulant.

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SUMMARY

Unprotected and protected N/P silicon and encapsulated cadmium sulfide solar cells were exposed to a simulated micrometeoroid environment. The degradation of the solar cells was determined by measuring the current-voltage characteristic curves of the cells before and after exposure to clouds of 6-micrometer silicon carbide particles accelerated to hypervelocities in a 3-inch (7.6-cm) shock tube. The characteristic curves were measured at an intensity of 140 milliwatts per square centimeter using either a carbon arc or a 1-kilowatt lamp. The experiments demonstrated that the degradation of N/P silicon cells covered by the thinnest quartz used (6 mil or 0.15 mm) was greatly reduced from the degradation suffered by unprotected silicon cells. The short-circuit current of protected N/P silicon cells only reduced to 0.95 of its initial value for exposure energies as high as 9 joules. The studies also demonstrated that encapsulated cadmium sulfide solar cells performed as well as protected silicon solar cells for exposure energies less than 0.5 joule, despite evidence of particle penetration of the encapsulant.

INTRODUCTION

In general, solar cells without cover plates degrade rapidly in the space environment near the earth (ref. 1). Among the environmental factors that contribute to this degradation are particle and photon radiation and micrometeoroids. The effects of each of these factors must be evaluated to provide accurate estimates of solar cell performance.

The effects of radiation on the performance of unprotected solar cells have been extensively investigated in the laboratory (refs. 2 and 3). The rates of degradation and the mechanism are now known. For example, the effects of radiation on solar cell performance can be reduced if cover plates of various types and thicknesses are added

to absorb the harmful radiation. Silicon cells with cover plates have been used success-
fully as power supplies for many satellites. However, because of the increase in weight
due to the cover plates, considerable research is now being devoted to developing
radiation-resistent cells (refs. 4 and 5) with either thin integral cover plates (ref. 6) or
semiorganic spray coatings (ref. 7). In addition, much effort is being devoted to the
development of thin-film solar cells such as the cadmium sulfide cell.

In contrast, little attention has been given to possible harmful effects on cell perfor-
mance resulting from bombardment by high-speed micrometeoroids in near-Earth space.
Therefore, the work reported herein was undertaken to investigate and isolate such
possible effects by exposing both covered and uncovered N/P silicon and encapsulated
cadmium sulfide solar cells to a simulated micrometeoroid environment.

SYMBOLS

$$E = \sum_{1}^{N} 1/2\left(m_i v_i^2\right)$$ total kinetic energy of particles striking 1- by 2-cm area

I_{sc} short-circuit current before exposure

I'_{sc} short-circuit current after exposure

m_i mass of impacting particle

v_i particle velocity

τ_E transmittance after exposure

τ_0 transmittance before exposure

EXPERIMENTAL APPROACH

Standard unshielded and shielded 1- by 2-centimeter N/P silicon solar cells (with
cover plates of various types and thicknesses) and developmental cadmium sulfide solar
cells, encapsulated in 1-mil- (0.025-mm-) thick H-film and Mylar, were bombarded by
clouds of 6-micrometer-diameter silicon carbide particles accelerated to hypervelocities
in a shock tube. The number, size, and velocity of the particles were measured so that
the total kinetic energy of the cloud of particles striking the cell could be used to char-
acterize the exposure (ref. 8). The total exposure energies used herein are the sum of
the energies of successive exposures in the shock tube. Before such an approach was
used, the degradation resulting from several exposures was shown to be the same as

that from a single exposure of equal total energy.

The 2- to 14-micrometer silicon carbide particles were accelerated to 2.65 kilometers per second in an attempt to simulate the near-Earth micrometeoroid environment. Nilsson and Alexander (ref. 9) reported that OGO-I measured micrometeoroid velocities in near-Earth orbit of 4.7 to 4.8 kilometers per second. These speeds are considerably lower than the average speed of 30 kilometers per second assigned to micrometeoroids in reference 10. The measured speed of reference 9 is comparable to that obtained in the Lewis shock tube. Hence the data presented herein can only at present be considered to be representative of the lower velocity micrometeoroids in near-Earth space. The bombarding particles had sufficient velocity (2.65 km/sec) to produce hypervelocity-impact effects in metals (refs. 8, 11, and 12). For such impacts, the craters formed in the metal target are hemispherical and larger than the impacting projectile diameter. For example, at 2.65 kilometers per second, the crater diameter in metal is $1\frac{1}{2}$ times as large as the projectile (ref. 11). Although the phenomena in glass type materials are not the same as in ductile materials, the craters formed in the glass appear hemispherical, but the lip that appears above the surface of the target material was not as pronounced as with metals. The nature of the craters formed can be seen in the photomicrograph in figure 1 (×300) of a quartz cover plate after exposure to 0.57 joule. The crater hole diameters are about the same size as that left in a metal target bombarded with the same particles and at the same speeds. The crater is, as in the case of the metal, $1\frac{1}{2}$ times as large as the impacting projectile. However, even though hypervelocity impact appears to have been achieved at a velocity of 2.65 kilometers per second, as evidenced by the similarity of the craters, at the present time there are no other data or criteria available which show that the phenomena in a semi-infinite glass target will remain the same at higher velocities. In the present study, the particle mass and velocity were such that the 60-mil (1.5-mm) quartz cover appeared as a semi-infinite target to the impacting projectile. For the Mylar and H-film materials (25 μm), the 2- to 14-micrometer silicon carbide particles used in this experiment can almost penetrate these materials on the first particle exposure because the particle size is comparable to the thickness of the materials. These surfaces do in fact become penetrated on successive exposures as a result of the probability of multiple hits on the same area. Increasing either the particle mass or velocity will probably increase the resultant rate of degradation not only because of an increased eroded area but also because of the increased probability of penetration by the particles.

The degradation of solar cells was determined by measuring the current-voltage characteristic curves before and after exposure to the particle clouds. The short-circuit current determined from these curves was the parameter chosen to describe the solar cell degradation. Almost all the current-voltage curves were measured with the carbon-arc solar simulator described in reference 13. However, to eliminate

possible errors due to the short-term instability of the carbon-arc lamp, characteristic curves for silicon cells with 6-mil- (0.15-mm-) thick quartz cover plates were also measured with a 1-kilowatt quartz-iodine tungsten-filament lamp. The lamp irradiated the solar cells directly without the collimating optics used with the carbon arc.

The total incident intensity was set at 1 solar constant (140 mW/cm^2) by a calibrated thermopile. A thermopile placed next to the test mounting plate was also used to maintain a constant intensity during the measurement of the cell characteristic curves. In addition, calibrated solar cells were used periodically to ensure a constant irradiance at the test position. The cell mounting plate was water cooled to maintain a constant plate temperature of 25° C.

The cell characteristic curves were determined by use of a two-wire (fig. 2(a)) and a four-wire (fig. 2(b)) electrical circuit. The two-wire circuit was easier to use, but the additional voltage drop across the lead wires could have caused an erroneous cell voltage measurement. The circuit with four wires was used as a check. The characteristic curves were recorded on an X-Y-plotter and were independent of the circuit used.

The cadmium sulfide cells were protected from possible harmful effects due to moisture (ref. 14) by storage in a desiccator when they were not in use. In addition, all measurements were made with the cells in a dry nitrogen atmosphere. As a safeguard, the characteristic curve for an unexposed control cell, treated in the same manner as the test cells, was measured at frequent intervals; no effect of moisture was found for this type of handling.

For determining whether or not any of the conditions in the shock tube, other than the particles, would affect cell performance, protected and unprotected N/P silicon cells and encapsulated and unencapsulated cadmium sulfide cells were exposed to the shocked gas alone. No changes in cell characteristics were found for the unprotected silicon cells, the protected silicon cells, or the encapsulated cadmium sulfide cells. However, the electrical characteristic for the unencapsulated cadmium sulfide cell changed, and therefore these cells were not considered further.

RESULTS OF LABORATORY EXPERIMENTS

Figure 3 shows typical characteristic curves for an unprotected N/P silicon solar cell exposed to particle energies ranging from 0 to 0.316 joule for an incident intensity of 140 milliwatts per square centimeter. For exposure energies of 0.131 and 0.316 joule, the characteristic curve was linear and the slope changed. The slope of the linear characteristic for an exposure of 0.316 joule was less than that for an exposure of 0.131 joule. According to the data presented in reference 15, such a change in slope may be indicative of an increase in the internal resistance of the solar cell. Such a change could be caused by surface cracks which would increase the sheet resistance of the cells. However, after

each exposure, the cells were examined under a microscope (×300), and no surface cracks were found. The change in the characteristic curve must then have been caused by a change in sheet resistance, which results from the cratering by the hypervelocity particles.

The ratio of the short-circuit current after exposure I'_{sc} to the short-circuit current for zero (initial) exposure I_{sc} is shown in figure 4 for N/P silicon cells with various types and thicknesses of cover materials (quartz, microsheet, and sapphire). Note that some of the points represent single exposures, and some represent the total energy of several smaller exposures. The unprotected cells degraded to 0.07 I_{sc} after exposure to 0.316 joule. For cells with cover plates, the short-circuit current apparently degraded less than 10 percent for energies as high as 1 joule. In addition, the degradation was independent of cover material for the materials and thicknesses investigated. The degradation curve for exposure energies greater than 1 joule was defined by exposing solar cells with 6-mil (0.15-mm) quartz cover plates to energies as high as 8.9 joules, as shown in figure 5. The short-circuit-current ratio reduced slowly to 0.95 I_{sc} at an exposure energy of about 5 joules, with no further change occuring for higher exposure energies.

The characteristic curves for an N/P silicon cell with a 6-mil (0.15-mm) quartz cover plate are shown in figure 6. These curves were obtained with a 1-kilowatt lamp. Since the characteristic curves obtained with the carbon arc are similar to those of figure 6, they are not shown in the figure. The short-circuit current and open-circuit voltage decreased slightly for an exposure of 8.92 joules. However, unlike the characteristic curve of the unprotected N/P silicon cell, the shape of this curve remained the same. According to reference 15, if the characteristic curves can be superposed by translation, the change can be attributed to a reduction of the light intensity incident on the sensitive surface of the solar cell. In fact, since the short-circuit current varies linearly with light intensity (ref. 15), the short-circuit current might be expected to vary linearly with effective transmittance of the solar cell. When the characteristic curves presented in figure 6 were translated vertically and horizontally, they were closely superposed. This close superposition tends to verify that the change in the characteristic curves due to micrometeoroid impaction was caused by a change in the intensity of radiation reaching the solar cell proper as a result of a reduction in cover plate transmittance.

In an effort to verify this conjecture further, a 60-mil- (1.52-mm-) thick quartz cover plate was successively bombarded and its change in transmittance with exposure energy obtained. Spectral transmittances were measured in an integrating sphere reflectometer. These values were then integrated with respect to the solar spectrum over the wavelength region (0.4 to 1.1 μm) of solar cell spectral sensitivity to obtain an effective transmittance. The integrated transmittance ratios are shown in figure 7. The transmittance decreases until an exposure energy of about 1.5 joules is reached and then remains constant for a further increase in exposure. This is the proper trend;

however, small differences (<0.10) exist between the short-circuit-current ratios and the transmittance ratios. These differences were expected and may be present for a number of reasons. For example, a difference between the carbon-arc spectrum and the solar spectrum exists; uncertainties in the total intensity incident on the solar cell and its uniformity are present; and multiple reflections are possible when the cover plate is attached to the solar cell. All these effects could easily account for the differences noted. The important point is that the general trends of the curves do agree. The conclusion, therefore, is that the decrease in cell short-circuit current results from the decrease in the effective transmittance of the quartz cover plates.

Typical characteristic curves (before and after exposure) for a cadmium sulfide solar cell encapsulated in 1-mil- (0.025-mm-) thick Mylar are presented in figure 8. The characteristic curves for the solar cell encapsulated in 1-mil- (0.025-mm-) thick H-film are similar in shape to those of the Mylar and are not shown. The curves in figure 8 cannot be superposed by a simple translation as the curves for protected silicon were. Because some particle penetration did occur, the degradation was probably the result of both a reduction in cover material transmittance and internal damage to the cadmium sulfide cell caused by the particle penetration.

The ratio I'_{sc}/I_{sc} for cadmium sulfide solar cells is shown in figure 9. The H-film encapsulated cells degraded more rapidly than did the Mylar encapsulated cells up to an exposure energy of 4.5 joules. From 4.5 to 6 joules, the current ratios remained the same for both types of encapsulants.

A comparison of figure 9 with figure 5 shows that the cadmium sulfide cells degraded more rapidly than the N/P silicon cells with cover plates. For instance, at a 5-joule exposure, the cadmium sulfide short-circuit current reduced to 0.36 I_{sc}, while the protected (6-mil or 0.15-mm quartz-cover) silicon cell reduced to only 0.95 I_{sc}. Since part of the reduction in the short-circuit current for the cadmium sulfide cell was thought to result from particle penetration, plastic covers of sufficient thickness, to preclude particle penetration, may offer significant improvement in the cadmium sulfide cell performance but with a severe weight penalty.

COMPARISON OF GROUND AND SPACE EXPERIMENTS

Making quantitative comparisons between ground and space experiments necessitates that the conditions of the experiments be similar and that the type of measurements be the same. For example, laboratory experiments showed that the characteristic curve of an unprotected N/P silicon cell became linear after exposure to micrometeoroids. If one assumes that this linearity might occur in a space experiment, it becomes apparent that the short-circuit current cannot be determined with certainty by measuring the current through a fixed load resistance. In fact, since the linearity of the degraded cells apparently changes (see fig. 3), the current through a fixed load resistance does

not degrade in the same manner. Unfortunately, the actual short-circuit currents of solar cells in near-Earth space (up to 1000 miles or 1610 km above the Earth) have not yet been measured. Hence, no quantitative comparisons can be made between solar cells used in labortory experiments with similar solar cells flown in near-Earth space.

However, the time in space for a given amount of cell degradation can be predicted from available experimental micrometeoroid space data used in conjunction with the laboratory data obtained on solar cells. Such a prediction is possible if the laboratory energy in joules is transformed to the actual time in space by use of flux data obtained from various rocket and satellite experiments. Unfortunately, this environment is not well defined (ref. 16) because of the many difficulties involved in obtaining and reducing satellite micrometeoroid data. Consequently, a number of micrometeoroid flux models have been proposed none of which have been corrorborated to date. The satellite experiments reported in reference 17, however, indicate the micrometeoroid flux to be low. As a result, the conservative micrometeoroid flux model of reference 18 was used herein as an approximation of the time in space associated with the laboratory exposure energies. This flux model and the method of reference 19 were used to find the total kinetic energy of microparticles in space striking a 2-square-centimeter area, and it was found that 0.0021 laboratory joule equals 1 space day (0.762 laboratory J/yr). It should be noted that when this calculation was made, no account was taken of Earth shielding or surface orientation. The following table gives the times in space calculated for a reduction from micrometeoroids alone to 0.95 I_{sc} using the micrometeoroid flux model of reference 18.

Type of cell	Laboratory energy needed for reduction to 0.95 I_{sc}, J	Equivalent time in space, day
N/P silicon (protected)	4.0	1935
N/P silicon (unprotected)	.01	2
Cadmium sulfide (Mylar encapsulated, 1-mil (0.025-mm) thick)	.25	120
Cadmium sulfide (H-film encapsulated, 1-mil (0.025-mm) thick)	.20	96

Note that the time calculated for a protected N/P silicon solar cell to degrade to 0.95 I_{sc} was long compared with the times calculated for the other types of cells listed in the table. The time for a cadmium sulfide solar cell encapsulated in 1-mil- (0.025-mm-) thick Mylar to reduce to 0.95 I_{sc} was approximately 1.25 times as long

as that for a cadmium sulfide solar cell encapsulated in 1-mil- (0.025-mm-) thick H-film. Although it is not possible to predict the actual time required for a reduction in cell performance to a given level because of the uncertainty in the micrometeoroid flux, the laboratory data converted to time in space does indicate that protection of solar cells from micrometeoroids may be needed and consequently must be given attention. Furthermore, because the reduction of short-circuit current for a protected N/P silicon cell is small and the calculated degradation time, based-on a conservative flux model, is long, the use of a protected N/P silicon cell is apparently precluded as a means of detecting or drawing any conclusions about the micrometeoroid environment.

SUMMARY OF RESULTS

A laboratory study of the degradation of solar cells due to bombardment by simulated micrometeoroids gave the following results:

1. Unprotected N/P silicon cells were rapidly degraded by the simulated micrometeoroid environment. However, covering these cells with the thinnest of the quartz plates (6 mil or 0.15 mm) greatly reduced the damage. Changing the cover material to microsheet or sapphire or increasing the thickness to 60 mils (1.52-mm) gave no additional protection against the laboratory exposure.

2. The short-circuit current of an N/P silicon cell with a 6-mil- (0.15-mm-) thick quartz cover only reduced to 0.95 of its initial value after a total exposure of 5 joules. Further exposure to the simulated micrometeoroid environment caused no further reduction in the short-circuit current. Hence, no conclusions could be drawn about the micrometeoroid environment in space from the behavior of the short-circuit current of protected silicon solar cells previously flown in space.

3. The effective transmittance of the quartz cover plate degraded in a similar fashion to the cell short-circuit current. Therefore, it was concluded that the degradation in an N/P silicon cell short-circuit current was caused by the decrease in the effective transmittance of the quartz cover plate.

4. A cadmium sulfide solar cell encapsulated in 1-mil- (0.025-mm-) thick Mylar performed as well as an N/P silicon cell with a 6-mil- (0.15-mm-) thick quartz cover plate for exposure energies less than 0.5 joule. However, for exposure energies greater than 0.5 joule, the protected silicon cell maintained a much higher short-circuit ratio. A 1-mil- (0.025-mm-) thick Mylar encapculant afforded slightly more protection from

the micrometeoroid bombardment than did the 1-mil- (0.025-mm-) thick H-film encapsulant for exposure energies less than 5 joules.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, August 26, 1968,
            124-09-15-01-22.

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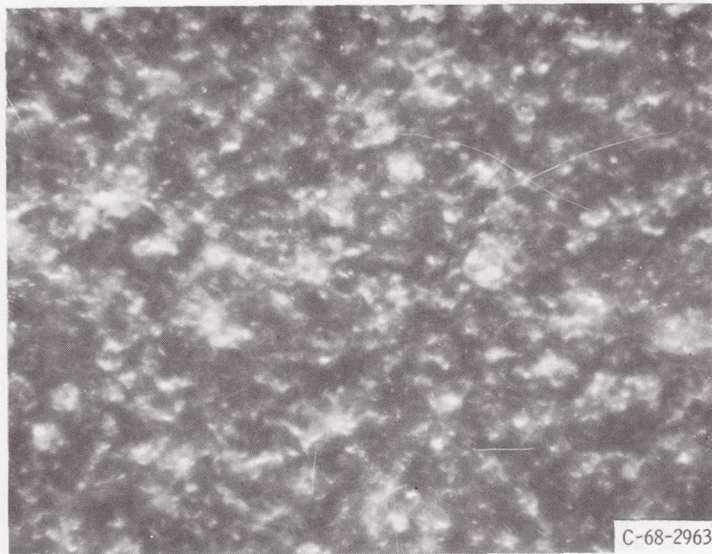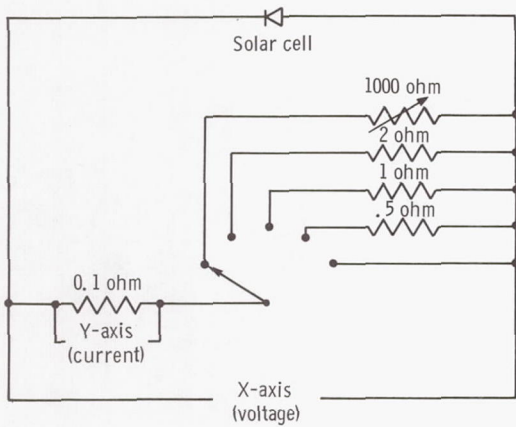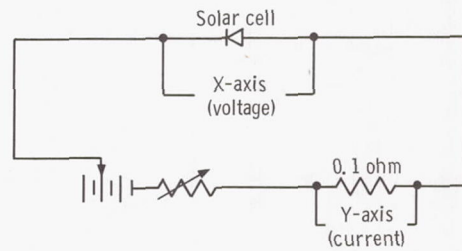
Figure 1. - Quartz cover plate after exposure to 0.57 joule. X300.

(a) Two-wire resistive-loaded circuit.

(b) Four-wire voltage-biased circuit.

Figure 2. - Electrical circuits used for measurements of solar cell current-voltage characteristic curves.
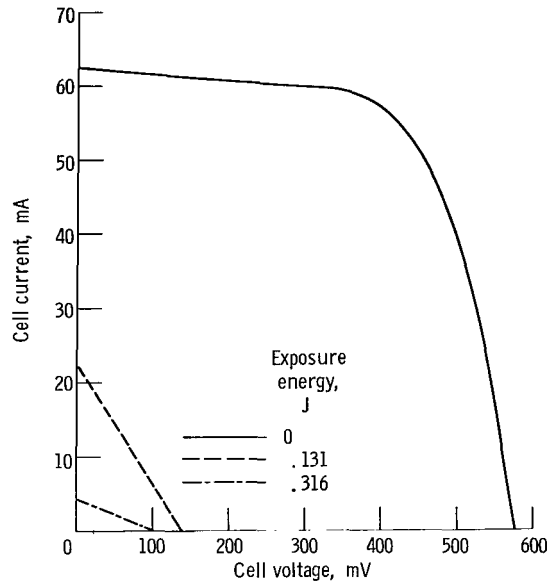
11

Figure 3. - Typical characteristic curves of unpro-
tected N/P silicon solar cells before and after ex-
posure. Carbon-arc solar simulator at total in-
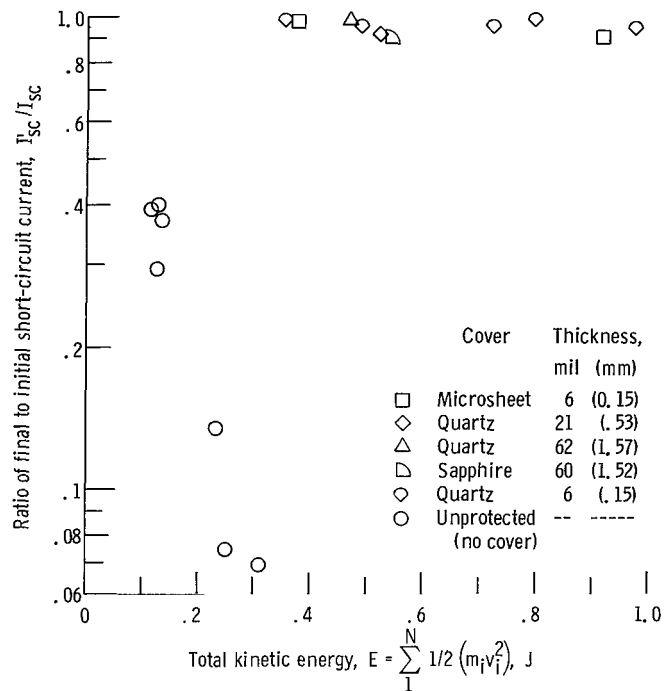cident intensity of 140 milliwatts per square
centimeter.

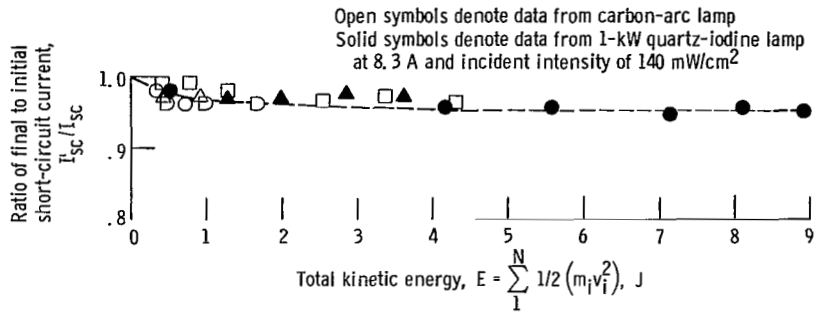Figure 4. - Degradation of N/P silicon solar cells due to particle
impact.

Open symbols denote data from carbon-arc lamp
Solid symbols denote data from 1-kW quartz-iodine lamp
at 8.3 A and incident intensity of 140 mW/cm^2

Ratio of final to initial short-circuit current, I_{SC}'/I_{SC}

1.0

.9

.8

0   1   2   3   4   5   6   7   8   9

Total kinetic energy, $E = \sum_{1}^{N} 1/2 \left(m_i v_i^2 \right)$, J

Figure 5. - Degradation of a number of 6-mil- (0.15-mm-) quartz-covered N/P silicon solar cells due to particle impact.

Cell current, mA

60

50

40

30

20

10

0

-100   0   100   200   300   400   500   600

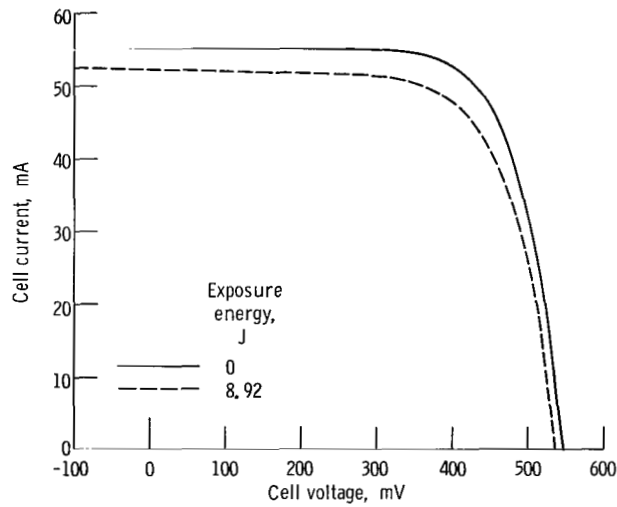Cell voltage, mV

Exposure
energy,
J

——— 0
– – – 8.92

Figure 6. - Typical characteristic curves of 6-mil- (0.15-mm-) thick quartz-covered N/P silicon solar cell before and after exposure. Total incident intensity of 1-kilowatt lamp, 140 milliwatts per square centimeter.
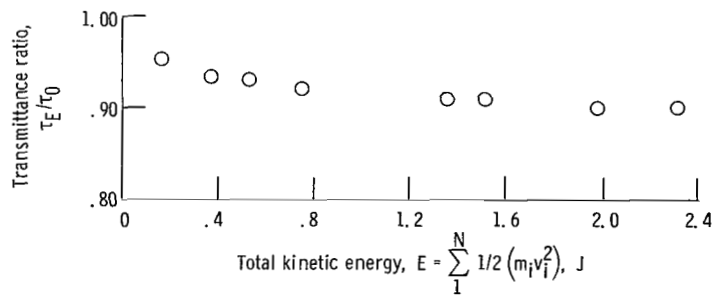
Transmittance ratio, τ_E/τ_0

1.00

.90

.80

0   .4   .8   1.2   1.6   2.0   2.4

Total kinetic energy, $E = \sum_{1}^{N} 1/2 \left(m_i v_i^2 \right)$, J

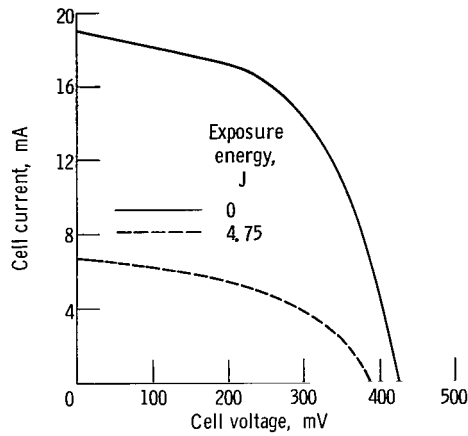Figure 7. - Degradation of 60-mil- (1.52-mm-) thick quartz cover plate due to particle impact.

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Figure 8. - Typical characteristic curves for
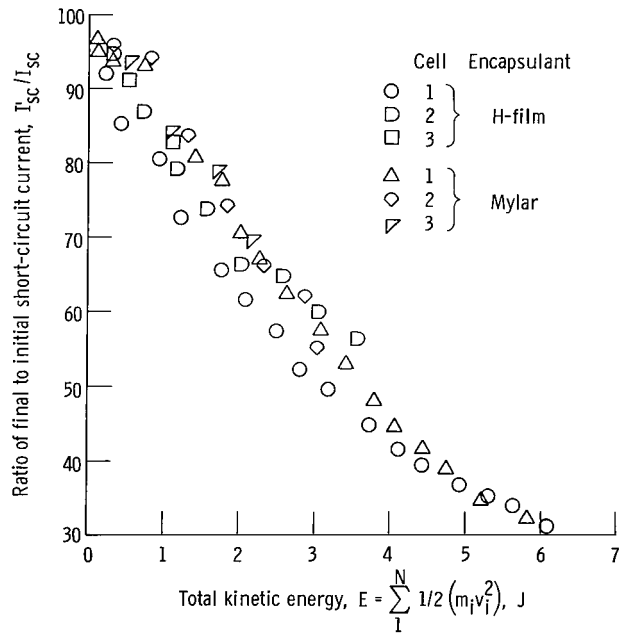Mylar-encapsulated CdS solar cell before
and after exposure to particle clouds.

Figure 9. - Degradation of encapsulated CdS solar cells due to
particle impact. Encapsulating material thickness, 1 mil
(0.025 mm).

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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